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Material Characterization and the Effects of Moisture and Drying on Injection Molded Torlon 5030

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Material Characterization and the Effects of Moisture and Drying
on Injection Molded Torlon 5030

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Abstract

In today's engineering design atmosphere a great deal of attention is be paid to optimizing manufacturing processes and components in a wide range of applications. One such area is the use of composite materials to replace metals such as aluminum. More specifically, injection molding of composites can dramatically drive down costs when producing components on a mass production scale rather than machining intricate parts from bulk metal. The major benefit of injection molding is that one can manufacture a part that has a more optimized and complex design without paying the higher associated machining costs and longer leads times. This allows for more optimized designs, which can lead to significant reductions in both the cost and weight of components.

As a result of sponsor interest in using Torlon 5030, the objective of this work was to define relevant properties for their application criteria and conduct relevant product tests. The application required the product to operate between -50 and 350°F. The component would also be exposed to water and Jet A. It would have to have good sliding wear characteristics and strength requirements associated with fracture due to overload, fatigue, and creep. Accordingly, with consultation with Dr. Eric Jordan, a test plan was developed that identified the relevant properties and studies were then completed in these critical areas.

Injection molded Torlon 5030, a high performance molding plastic fabricated by Solvay Specialty Polymers was exclusively studied in this paper. To begin, baseline testing was conducted at the University of Connecticut to confirm that all test samples met the material properties as described by the vendor and that proper test methods could be repeated. After confirming the baseline data, exploratory testing was conducted in

areas not described in the supplier's design guide. This included wear, creep, and fatigue tests as well as the effects of water and Jet A exposure on the material properties. One of the principle results of this work is a realization that water exposure and wear are the most problematic performance metrics. Finally, the work also explores possible avenues to prevent or reverse tensile strength degradation due to water exposure.

1.0 Introduction

As just discussed, a significant portion of engineering design work focuses on weight and cost reduction in components especially found in the aerospace and automotive industry. There has been a significant shift in moving from solid metal components to composites. Composites can most generally be described as a single medium that consists of two or more separable materials that are combined on a macroscopic scale [1]. A key advantage to composites is that the combination of the two or more materials typically leads to a significant increase in the specific strength (ratio of tensile strength to density) compared to the single material alone. There are three main types of composites: fibrous, laminated, and particulate [2]. Torlon 5030, which is exclusively studied in this paper, is classified as a fibrous composite. More specifically, Torlon 5030 is a short, or chopped, fiber composite set in a thermoplastic base resin.

Torlon is a polyamide-imide (PAI) base resin which can also be filled with glass or carbon fibers. Specifically, the 5030 blend contains 30% glass fibers by weight. It is typically used in applications where high stiffness, good retention of stiffness at elevated temperatures, very low creep, and high strength are desired.

Common applications include: aircraft hardware and fasteners, mechanical and structural components, transmission and powertrain components, as well as bearing

retainers. It is also resistant to most strong acids and organics, making it an ideal high performance plastic for a wide variety of application environments [3].

Extensive details on mechanical, thermal, and friction and wear properties can be reviewed in the *Torlon Design Guide* provided by Solvay [4]. While quite thorough and accurate, the guide does not emphasize the effects of water on the tensile strength of Torlon 5030.

In our case, Torlon 5030 was desired to replace aluminum in high temperature applications up to 350°F. The goal was to use injection moldable composites to manufacture more complicated geometries, which ultimately would result in a more optimized design driving down cost and weight. The key in switching over to 5030 was to not lose any of the structural capabilities of aluminum 6061 T6, even when operating near 350°F temperatures.

Two of the most critical aspects of the application were to have a high creep resistance and also retain its mechanical properties when exposed to natural weather elements for a period of 10-15 years.

2.0 Experimental Methods

The majority of testing conducted in this study involved 6.5 inch long, 0.125 inch thick injection molded Torlon 5030 tensile bars received from Solvay Specialty Polymers. The tensile bar geometry follows ASTM D638 Type 1. It should also be noted that the tensile bars were post-cured after injection molding for a period of 17 days per the design guide. Unless otherwise stated, the injection flow of material was in the longitudinal direction of the tensile bar. This is the preferred fiber orientation for maximum mechanical properties.

The following arrays of tests were all conducted at the University of Connecticut. Tensile strength testing was completed using an Instron Universal Tester model 5869. Testing was conducted by following the procedures described in ASTM D638.

Creep testing was conducted using a lever arm creep tester, model 2320, manufactured by Applied Test Systems (ATS). Again, an ASTM D638 Type 1 tensile bar was used in this experiment.

Fatigue testing was done on an Instron model 1350 test machine using the Fast Track 8800 software. Stress was computed from ram displacements. The test was conducted at three different stress levels with an R-ratio of 0.1 and at a frequency of 15 Hz. ASTM D638 tensile bars were used.

High temperature water exposure testing was done using a RITE-HETE WB70 water bath. ASTM D638 tensile bar samples were stored in sealed glass containers filled with distilled water. The glass containers were then inserted into the larger heated water bath, which was maintained at 176°F. Samples were dried in a Binder FP-90 circulating air oven.

Wear testing was completed using a Falex Multispecimen Test Machine. A small thrust washer of the wear material was run in a circular manner against the base bearing material, in this case, Torlon 5030. ASTM D3702 was followed. An air compressor and air line was integrated into the machine to allow for longer test times that would be possible with bottled gas that was previously used.

Additionally, testing was conducted in a humidity chamber located off campus. The chamber was cycled daily between 86 and 140°F while being held constantly at 95% relative humidity.

Metallization of test samples were conducted at Epner Technology Incorporated located at 78 Kingsland Avenue in Brooklyn, New York.

3.0 Results

This section details testing that was performed at the University of Connecticut in order to reproduce data found in the *Torlon Design Guide* provided by Solvay Specialty Polymers [4]. This was first done to ensure that the quality of materials being tested were an accurate representative batch of samples from the supplier. Testing was conducted in selected critical property areas such as tensile strength and creep performance. Additional testing was then conducted to provide critical data that is not currently available in the design guide. This includes data related to water and fuel exposure as well as wear testing. The entire test program was decided upon with little supervision from the industrial sponsor. UConn was in charge of identifying any possible problems and then providing solutions to any issues discovered. A complete log of data for the relevant test cases can be found in the appendix.

3.1 Baseline Tensile Strength

The first area of testing was to attempt to replicate the tensile strength data provided by the material supplier, Solvay. The goal in doing so was to ensure that an accurate representative batch of samples was being evaluated and that testing procedures could be completed successfully and repeatedly. The tensile strength of Torlon 5030 at room temperature according to Solvay's *Torlon Design Guide* is 32.1 kpsi per ASTM D638. Similarly, the average strain percent and tensile modulus is 2.3% and 2,110 kpsi respectively [4].

It should be noted that the tensile bar samples tested at UConn were first conditioned by drying them for 24 hours at 300°F, as recommended in the *Torlon Design Guide*. This was done to ensure that the samples did not contain any moisture. Following the 24 hours of drying at 300°F samples were then stored at room temperature in a sealed container with desiccants. Moisture plays a critical role in the mechanical properties of Torlon 5030 and will be discussed further.

Table 1 below summarizes the results of tensile testing a representative batch of five tensile bar samples conducted at UConn. As just discussed, the samples were dried prior to testing. The average tensile strength was 33.7 kspi with a standard deviation of 0.6 kpsi.

Table 1: UConn Tensile Data for Torlon 5030

Tensile Strength, kpsi	33.7 ± 0.6
Tensile Strain, %	2.62 ± 0.13
Tensile Modulus, kpsi	2098 ± 24

3.2 Longitudinal vs. Transverse Fiber Orientation

In conjunction with studying the baseline injection molded bars as discussed in the preceding section, the impact of fiber orientation was also examined. Injection molded sheets of Torlon 5030 were created with dimensions of 6 by 6 inches with a thickness of 0.125 inches. These sheets were molded at a different time and with a different injection molding geometry than the tensile bars described in the preceding section. As a result, the machined tensile bars are not expected to give identical properties even in the primary longitudinal injection molding direction. This is most likely due to the different degree of preferred fiber orientation in the wider sheet mold compared to the narrow tensile bar mold. Each molded sheet has a preferred direction of fiber orientation

that is created by the initial flow direction of the material into the sheet mold. ASTM D638 tensile bars were then machined out from the injection molded sheets in both the longitudinal and transverse flow directions. This allows for a study of the tensile strength of bars where the fiber orientation is in the longitudinal flow direction and also in the transverse cross flow orientation. Five samples were tested for the longitudinal direction and six samples were tested in the transverse fiber orientation direction. Table 2 summarizes the data.

Table 2: Fiber orientation impact on Tensile Strength

	Longitudinal	Transverse
Tensile Strength, kpsi	27.5 ± 1.5	21.2 ± 1.4
Tensile Strain, %	3.0 ± 0.2	2.4 ± 0.3
Tensile Modulus, kpsi	1522 ± 71	1231 ± 66

3.3 Creep Testing

For our application, creep properties were critical and also the limiting design factor. As a result, it was a priority to replicate creep data provided by Solvay. One of the best properties of Torlon 5030 is its exceptional creep behavior at both room and elevated temperatures up to 400°F. Our design temperature was 300°F. The goal of this test was to ensure that data provided by Solvay was accurate and to test the material at our design temperature as well as at our design stress of 5 kpsi.

A single tensile specimen was used and the test was conducted at 300°F. The sample was loaded to a stress of 5 kpsi. The duration of the test lasted approximately 600 hours.

Figure 1 is the plot for strain versus time of Torlon 5030 at 400°F as provided by Solvay [4]. In comparison, Figure 2 is the creep test that was conducted at UConn.

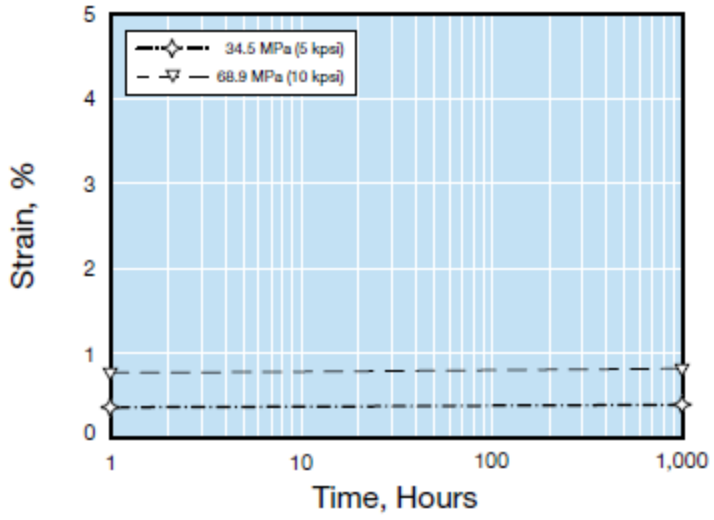

Figure 1: Solvay Creep Data (Solvay)

Based on Figure 1, one can estimate that at 400°F and an initial loading of 5 kpsi the strain is approximately 0.33%. Figure 2 displays the creep data that was compiled at UConn. The test was run at the same conditions as Solvay with the only exception of the temperature being at 300°F at UConn as opposed to 400°F at Solvay.

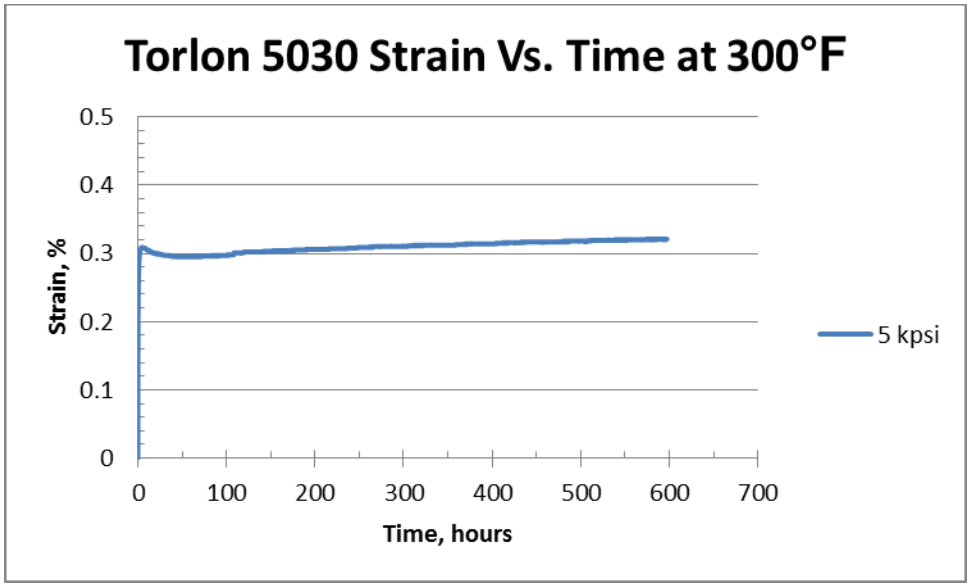

Figure 2: UConn Creep Data

The results proved to be nearly identical. After the initial loading of 5 kpsi, Torlon 5030 had a strain of 0.32%. After 600 hours the strain increased by 0.026%, following the same trend found in the *Torlon Design Guide.*

3.4 Fatigue Strength

Fatigue testing was performed to gain a better understanding of data found in the *Torlon Design Guide.* There is no supplier published data for the tension/tension fatigue strength of Torlon 5030. Flexural fatigue strength data for 5030 is available in the design guide at both room and 350°F temperatures and 30 Hz. From speaking with a materials engineer at Solvay, the tension/tension fatigue strength of Torlon 5030 is estimated to be roughly 10% less than that of Torlon 7130, the carbon fiber filled equivalent to 5030. Figure 3 below is the tension/tension fatigue data provided by Solvay for Torlon 7130 (carbon filled variety) at room temperature and 30 Hz. An R-ratio of 0.1 was used.

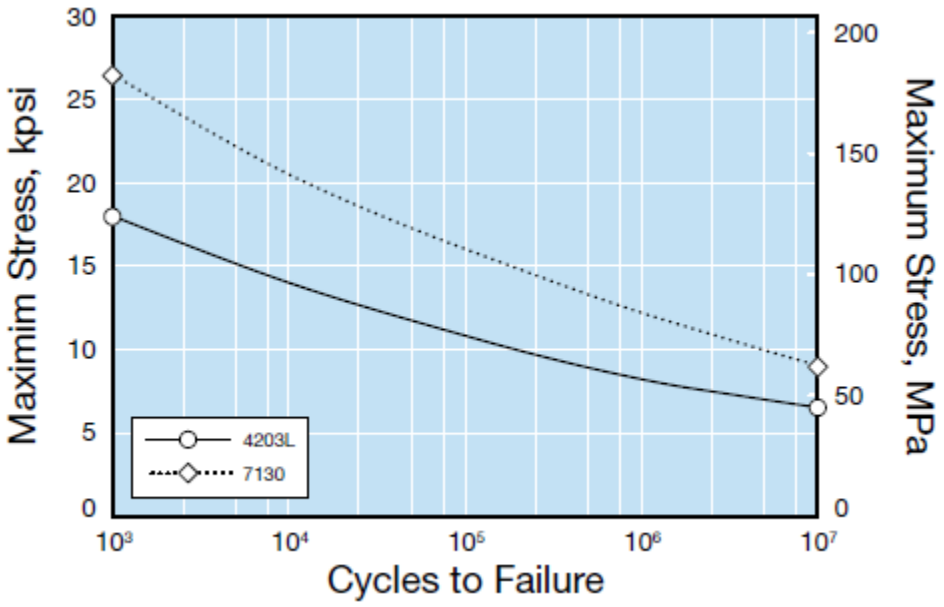

Figure 3: Tension/Tension Fatigue Data for 7130 (Solvay)

Due to equipment limitations at UConn, testing was run at a maximum stress of 12 kpsi and 15 Hz. Testing was also done at a stress level of 10 kpsi and 9 kpsi both at 15 Hz. Two tensile specimens were used at each stress level and the results were averaged together. Figure 4 illustrates the tension/tension fatigue performance of 5030 as run at UConn.

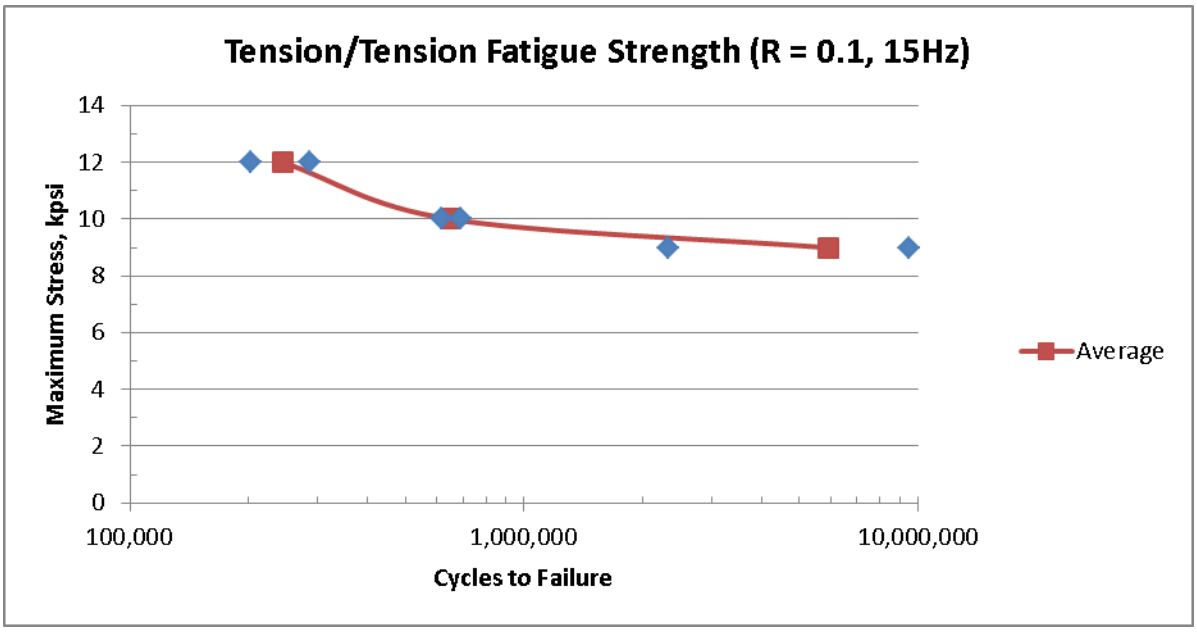

Figure 4: Tension/Tension Fatigue Testing at 15 Hz

3.5 Jet A Exposure on Tensile Strength

The effect of Jet A exposure on the tensile strength of Torlon 5030 was also investigated. To begin, six tensile bars were dried for 24 hours at 300°F. Upon completion, the bars were completely submerged into a container of Jet A. Samples were left soaking for various periods of time at room temperature. The samples were then removed and the surfaces of the bars were dried off with a towel. ASTM D638 tensile tests were performed on the bars. A summary of the results is located in Table 3. Three samples were tested at each weight gain interval. Again, the baseline tensile strength for

dry tensile bars not subjected to any moisture was 33.7 kpsi. A bar that was subjected to 22 weeks in Jet A had an average tensile strength of 33.4 kpsi with a standard deviation of 0.3 kspi.

Table 3: Jet A Exposure on Tensile Strength

Time, Weeks	Weight Gain, %	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
17	0.338	31.7 ± 0.9	2.36 ± 0.24	2094 ± 32
22	0.418	33.4 ± 0.3	2.75 ± 0.06	2101 ± 11
No Exposure	0.000	33.7 ± 0.6	2.62 ± 0.13	2098 ± 24

3.6 Water Absorption

As mentioned at the beginning of the paper, water absorption plays a critical role in the properties of Torlon 5030. Consequently, several absorption studies were conducted.

Similar to the majority of other materials, the rate of weight gain in Torlon is primarily dependent on the temperature of the environment. The maximum water content capable of being absorbed into the part is strongly linked to the relative humidity. Figure 5, provided by Solvay, illustrates the equilibrium water absorption vs. the relative humidity [4].

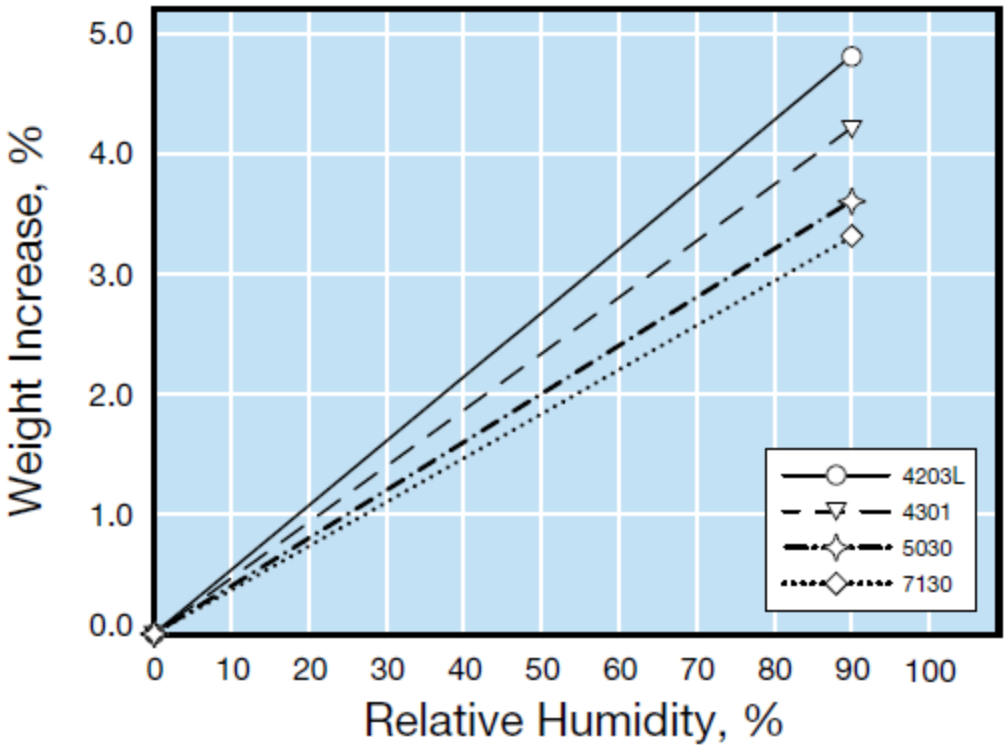

Figure 5: Equilibrium Water Absorption vs. Relative Humidity (Solvay)

Assuming a near fully saturated environment, Torlon 5030 will eventually reach an equilibrium water content of approximately 3.6% weight gain from its completely dried state.

The water absorption rates are quite slow for Torlon 5030 at room temperature and 50% relative humidity [4]. Even in extreme natural conditions the water absorption rates are slow. For example, at 110°F and 90% relative humidity, Torlon 5030 absorbs 2.5% weight gain after 100 days and then increases extremely slowly after that, as seen in Figure 6 produced by Solvay [4].

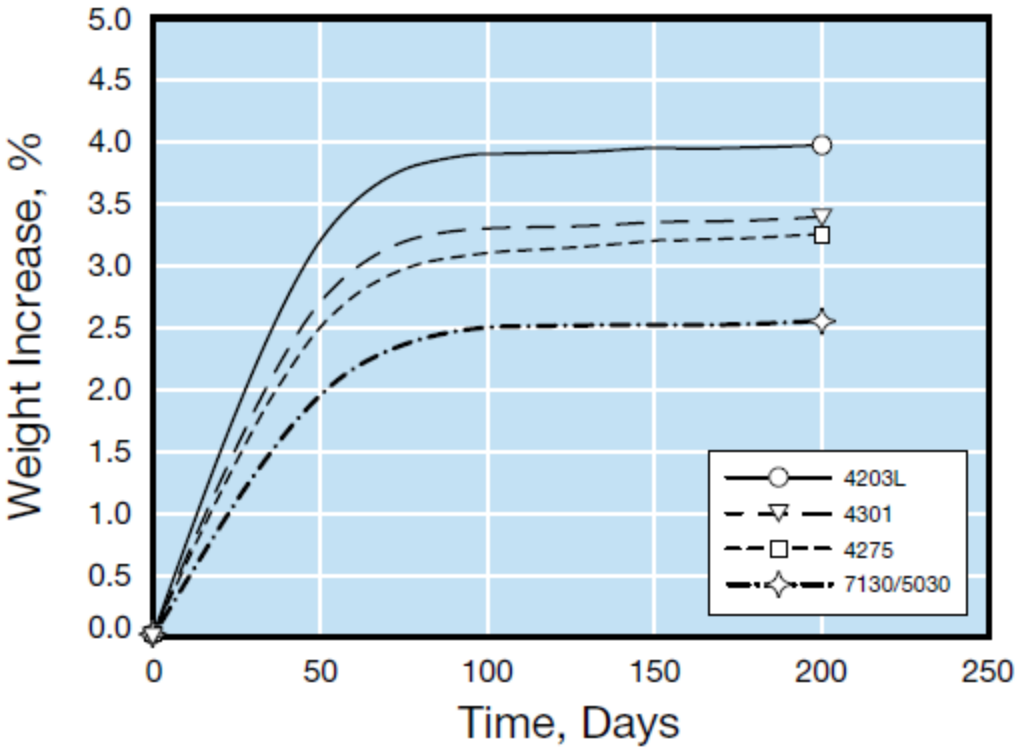

Figure 6: Water Absorption Rate at 110°F and 90% RH (Solvay)

As a result of the slow moisture absorption, most water absorption studies at UConn were conducted in an elevated temperature water bath to push the samples toward the equilibrium point more quickly. Samples were soaked directly in distilled water and the temperature was held constant at 176°F.

Figure 7 plots the water absorption kinetics produced at UConn for Torlon 5030 when exposed to 176°F compared to at room temperature. Three samples were soaked at each of the two temperature environments. Each data point consists of the average of the weight gain for the three bars. 60 data points were recorded for the water kinetics at 73°F and 31 data points for 176°F.

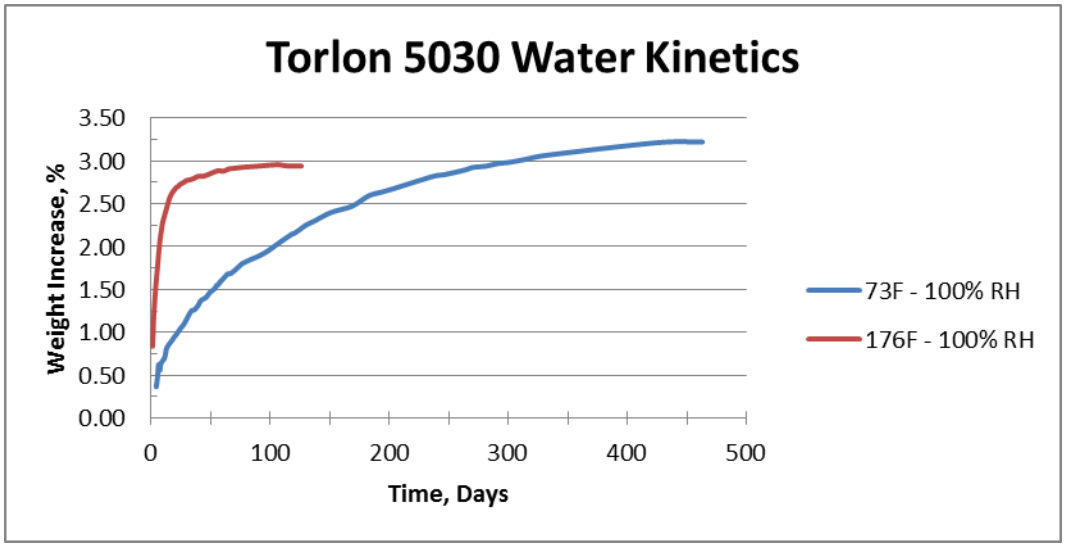

Figure 7: Water Absorption at 176°F and 73°F

3.7 Tensile Strength Degradation

As discussed earlier, the tensile strength of Torlon 5030 at room temperature is 33.7 kpsi. The next course of testing was to explore the impact that accumulated water moisture within the part would have on the tensile properties of 5030.

Samples were soaked to varying amounts in the 176°F water bath described in the preceding section. One such case included samples that had soaked for two weeks and accumulated an average 2.4% weight gain. The second case tested samples that had an average weight gain of 2.6% after five weeks. Tensile testing was then performed at room temperature on these samples with the same procedure as applied to the dry control samples. Table 4 compares the tensile properties with varying amounts of absorbed water. Five tensile bars were tested at each weight gain category. Samples exposed to a minimum of 2.4% weight gain had a 15% drop in tensile strength compared to the dry control samples.

Table 4: Tensile Strength Degradation due to Water Weight Gain

Weight Gain, %	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
0.00	33.7 ± 0.6	2.62 ± 0.13	2098 ± 24
2.40	28.7 ± 0.4	2.53 ± 0.10	2067 ± 23
2.63	28.7 ± 0.1	2.48 ± 0.08	2078 ± 15

3.8 Effects of Drying

3.8.1 Samples Pre/Post-Dried at 350°F

The purpose of this test was to explore how drying temperatures of 350°F impact the tensile strength of samples that were exposed to water at 176°F for a period of two and five weeks. With each test time, half of the samples were tested after only towel drying the surface and the other half were tested after drying in an oven for 24 hours at 350°F. Table 5 summarizes the average tensile strength of each of the four test cases. Three tensile bars were tested at each weight gain category.

Table 5: Drying Effects at 350°F

Time, Weeks	Weight Gain, %	Tested	Tensile Strength, Ksi	Tensile Strain, %	Tensile Modulus, kpsi
2	2.60	Wet	26.8 ± 0.0	2.57 ± 0.07	2054 ± 37
2	0.20	Post-Drying	31.7 ± 0.1	2.63 ± 0.07	2043 ± 29
5	2.88	Wet	26.6 ± 0.1	2.45 ± 0.04	2068 ± 40
5	0.46	Post-Drying	30.8 ± 0.5	2.45 ± 0.06	2048 ± 31
Baseline	0	Dry	33.7 ± 0.6	2.62 ± 0.13	2098 ± 24

Samples that were soaked for two weeks had gained, on average, 2.60% weight gain. The average tensile strength of these samples was 26.8 kpsi. However, after drying samples for 24 hours at 350°F and returning them to nearly their original weight, the average tensile strength recovered back to 31.7 kpsi compared to 33.7 kpsi for the non-soaked average. The dry baseline was initially dried for 24 hours and then store at room temperature in a container of desiccants.

The same procedure was conducted for samples soaking for five weeks. Again, from Table 5 above one can see that the tensile strength dropped to 26.6 kpsi (similar to the effects found at two weeks), but then recovered back closer to the dry baseline tensile strength upon drying in the oven.

3.8.2 Implications for Mechanisms

As just discussed, water does degrade the tensile properties of Torlon 5030 by at least 15%. However, upon drying, these properties can be returned closer to their original dried state. Water can affect the properties of Tolon by physical presence and/or by hydrolysis. Hydrolysis is not expected to be a very reversible process. Consequently, it is believed that the reversible degradation would signify that it is related more to the physical presence of water molecules in the material. Hydrolysis is not believed to be the primary degradation mechanism.

3.9 Blistering

Another concern related to the absorption of water by composite materials like Torlon is the possibility of blistering upon sudden exposure to heating. The absorbed water in Torlon limits the rate at which parts can be heated. Exposing Torlon parts that have absorbed water to sudden high temperatures (greater than 300°F) can cause parts to blister, or rupture open. Blistering will occur when water is not able to diffuse quickly enough from the part. Several configurations of tests were conducted to examine the possibility of blistering around our design temperature of 300°F.

3.9.1 Elevated Temperature Water Bath

The first configuration involved five tensile bar samples that were initially dried for 24 hours at 300°F. The samples where then inserted into the elevated temperature water bath at 176°F to accelerate the absorption of water. The samples were left in the water bath until they reached a water weight gain of 2.85%. This weight gain was selected to simulate a worst case scenario for the maximum amount of water weight gain that our application would see.

After achieving this weight gain, the five samples were immediately inserted into a preheated 325°F circulating air oven. Samples were left in the oven for a period of 24 hours. Upon removal, the samples were visually inspected for any signs of distortion or blistering. After close inspection, no signs of blistering were found for the five samples exposed at 325°F.

The second configuration involved another set of five tensile bars that once again were initially dried for 24 hours at 300°F. They were then inserted into the same elevated temperature water bath and submerged until they too gained 2.85% in water weight. In contrast to the previous configuration, these samples were immediately inserted into a preheated 350°F oven for 24 hours. However, similar to the samples at 325°F, no signs of distortion or blistering were observed.

3.9.2 Humidity Chamber

The next configuration looked at was tensile bar samples that were exposed to a humidity chamber as opposed to directly soaking in water. In this case, 10 tensile bars were inserted into a humidity chamber for a period of 110 days. The humidity chamber was held at a constant relative humidity of 95% while cycling between 86°F and 140°F

daily. Similarly, the samples remained in the chamber until they had a weight gain of 2.8%. They were then inserted into a preheated oven at 350°F and held there for 24 hours. After inspection of all 10 samples, none displayed signs of distortion or blistering.

3.9.3 Higher Temperatures and Larger Thicknesses

The next course of action was to explore the possibility of blistering in parts with larger thicknesses. The tensile bars had a uniform thickness of 0.125 inches. Similar tests were conducted as described above, but with thicker parts. A cylinder was used with a four inch long section with a radius of 0.75 inches.

Again, two samples were fully submerged in the 176°F water bath until they gained 2.8% in water weight. The first sample was then immediately inserted into a preheated 350°F oven for 24 hours. Upon removing the sample there were no signs of distortion or blistering.

The second configuration involved the other soaked cylindrical sample and inserting it into a preheated 400°F oven for 24 hours. The result was significant blistering across the entire sample. Figures 8 and 9 are pictures of the ruptured solid 0.75 inch diameter Torlon cylinder.

In order to verify that it was not just the larger thickness, three tensile bars were again soaked to 2.8% weight gain and inserted into the preheated 400°F oven for 24 hours. Similar to the Torlon cylinder, the tensile bars also blistered at the 400°F temperature. A comparison of a non-soaked vs. soaked tensile bar sample exposed to 400°F can be found in Figure 10.

Figure 8: Blistering at 400°F Exposure

Figure 9: Torlon 5030 Blistering

Figure 10: Soaked vs. Non-soaked Samples Exposed to 400°F

3.10 Metallization

In order to protect against water weight gain and the associated concerns regarding tensile strength degradation and blistering we next looked into metallizing the bare Torlon material. The intention was that the metal layer, which will be discussed in further detail, would act as a shield and prevent water from penetrating into the material resulting in the aforementioned damage. Simultaneously, the metal coating would act as an improved wear surface and serve as electromagnetic shielding.

A series of different metal thicknesses were applied to injection molded Torlon tensile bars. Metallization was completed at Epner Technology Incorporated in a process involving initial metallization by activated electro-less plating of copper followed by electroplating a top layer of nickel. Prior to being sent for metallization, the tensile bar samples were dried for 24 hours at 300°F. This was done to eliminate as much of the water inside the part as possible prior to plating.

A base layer of copper was chosen as it has a similar coefficient of linear thermal expansion (CLTE) as Torlon 5030. As described in the *Torlon Design Guide*, 5030 has a CLTE of 9 10^{-6} in/in°F. A topcoat of nickel was then applied over the copper as an extra sealant and better protector against corrosion. More specifically, the copper layer was applied to the Torlon surface electrolessly after chemically activating the surface. Subsequently, the nickel layer was electroplated to the base layer of copper.

Overall, four different copper-nickel thicknesses were each applied to five tensile bars. The metal thickness of copper and nickel are in thousandths of an inch. Figures 11 and 12 illustrate the five overall configurations and how they compare. These samples were then inserted into the 176°F water bath and their absorptions rates were continually

monitored and referenced against samples without plating. 12 data points were recorded for each of the four levels of metal plating. Each data point consists of the average of three tensile bars. The curve for water absorption with no plating contains 31 data points and is the average of three tensile bars. The standard deviation for no plating is ± 0.01%. The standard deviations in order of copper thickness starting with 1.0 mil are ± 0.08%, ± 0.07%, ± 0.04%, and ± 0.01% respectively.

Plating significantly reduces the amount of water absorbed in the material. However, water is still able to gain access through the plating. A couple theories are surface imperfections or roughness as well as pinholes created during the electro-less application of copper. Both of these theories are elaborated in the discussion section of this paper.

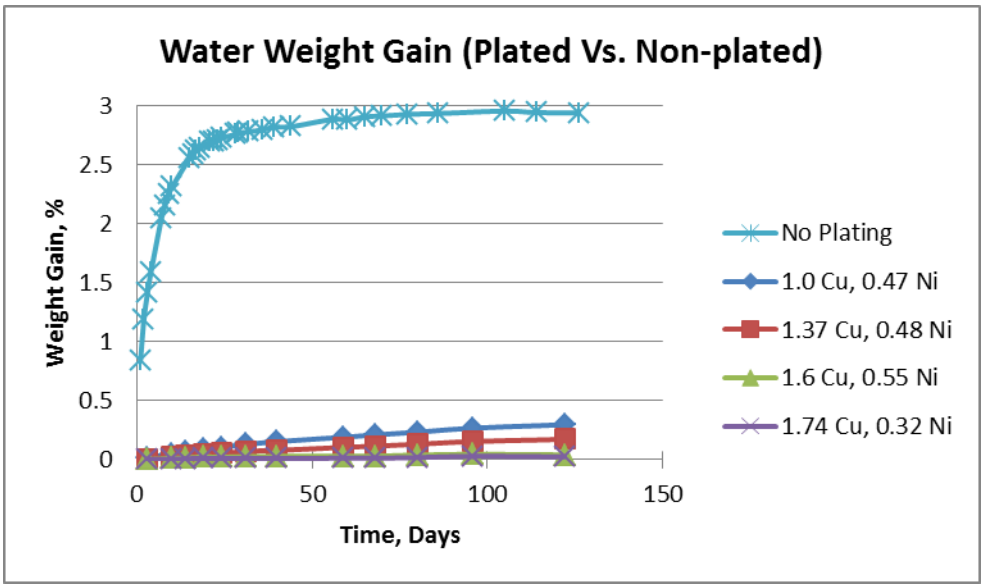

Figure 11: Plated vs. Non-plated Weight Gain

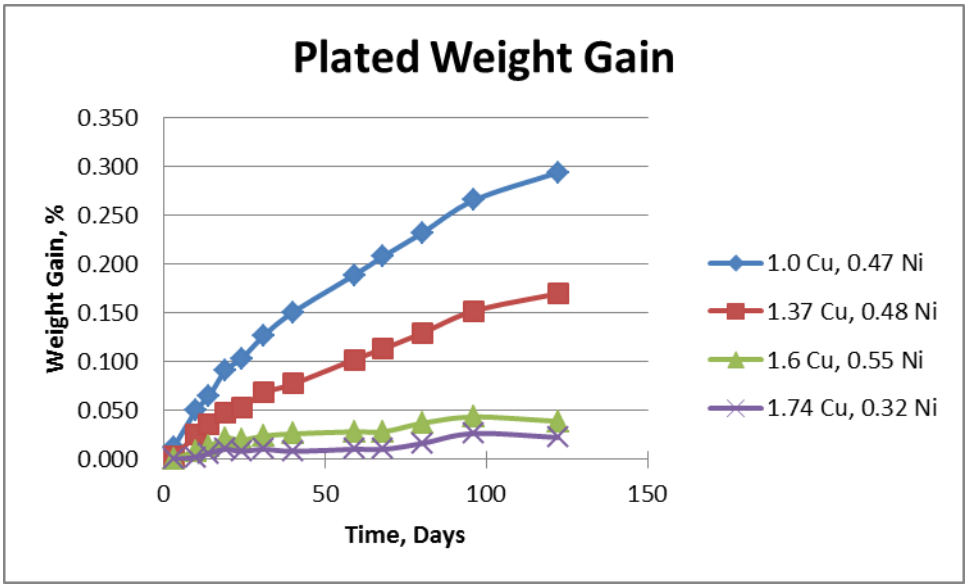

Figure 12: Plated Weight Gain

3.11 Wear Testing

The goal of wear testing was to explore the wear behavior of Torlon 5030 versus common metals, such as Aluminum 6061 T6. Our sponsor suggested two materials that were already characterized and approved when being combined with Aluminum, Rulon LR and Avalon 89.

The objective of this wear test was to directly compare wear performance of these two materials against both Torlon 5030 and Aluminum 6061 T6. The test was constructed to get a baseline wear performance of Torlon and learn if bare 5030 could be used as a wear surface.

Figure 13 illustrates the assembly of wear test pieces as described in ASTM D3702 [5]. The test consists of a test specimen, Avalon 89 or Rulon LR, to be run in a circular manner against the bearing material, Torlon 5030 or Aluminum. The test was run at room temperature and in a static solution of Isopar-M. Isopar-M offers the same lubricity characteristics as Jet A, but with a higher flash point temperature, making the

test safer. The P-V for Avalon 89 cases was 4,161 psi-fpm and 9,747 psi-fpm for Rulon LR cases.

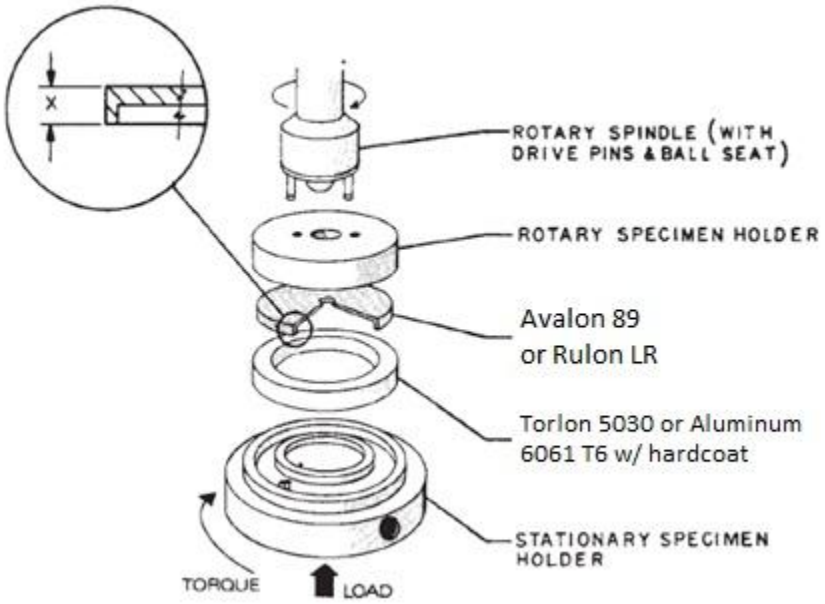

Figure 13: Wear Test Assembly

Figure 14 below illustrates the wear test setup. The arrow points to the test specimen (Avalon 89 or Rulon LR). The red star is the container that houses the static solution of Isopar-M. The bearing materials (Aluminum or Torlon) are located at the base of the fluid container. The Isopar-M fluid was kept to always submerge both the test specimen and bearing material throughout the course of the test.

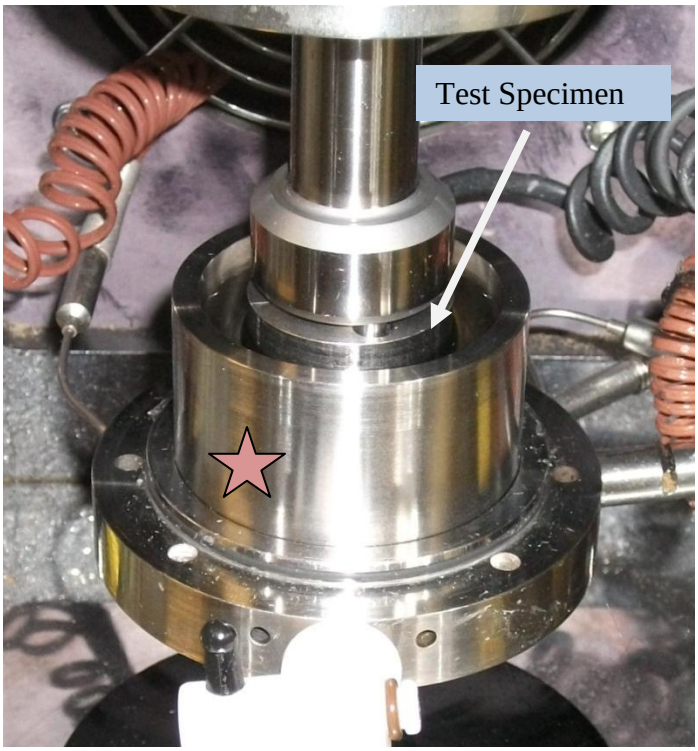

Figure 14: Wear Test Setup

Table 6 details the four testing configurations that were studied. Each test specimen material was run against both Torlon and Aluminum. Each case was also run three times.

Based on nine samplings, the Aluminum had an average Ra surface finish of 1.28 μm and the lay direction was circumferential in the direction of the wear path. Based on eight samplings, the Torlon had an average Ra surface finish of 0.497 μm. However, the lay direction was liner and was perpendicular to the wear path.

Table 6: Wear Test Configurations

Test Specimen	Bearing Material
Avalon 89	Torlon 5030
Avalon 89	Aluminum 6061 T6
Rulon LR	Torlon 5030
Rulon LR	Aluminum 6061 T6

The test process includes a 40 hour break in period and then a successive 100 hour test period. Wear measurements on the test specimen (Avalon 89 or Rulon LR) were made before and after each test interval using a micrometer and following ASTM D3702. A new Torlon or Aluminum disk was used for each 140 hour test.

Overall, Avalon 89 performed significantly better than Rulon LR on Torlon 5030. Table 7 summarizes the average wear rates for each of the four configurations.

Table 7: Wear Test Performance

		Wear Rates, microinches/hour		
Test Specimen	**Bearing Material**	**40 hour**	**100 hour**	**Overall**
Avalon 89	Torlon 5030	35.4	10.0	17.3
Avalon 89	Aluminum 6061 T6	25.0	10.8	14.9
Percent Difference (Torlon vs Alum)		***42%***	***-8%***	***16%***
Rulon LR	Torlon 5030	58.3	43.7	47.9
Rulon LR	Aluminum 6061 T6	47.9	25.8	32.1
Percent Difference (Torlon vs Alum)		***22%***	***69%***	***49%***

For example, Avalon 89 wears 42% faster in the initial 40 hour break-in test on Torlon 5030 than it does on Aluminum 6061 T6. However, in the following 100 hour test Avalon 89 wears 8% less on Torlon than Aluminum. Taking a sum over the entire 140 hour period Avalon 89 wore 16% slower on Aluminum than on the bare Torlon 5030.

Rulon LR performed worse as the wear testing continued. Rulon LR wore 22% faster on Torlon than Aluminum in the first 40 hour period; however it worsened in the following 100 hour period to wear 69% faster.

Table 8 summarizes the wear track depths that the test specimen created in the bearing material in micrometers. An average of three samples was taken for each configuration. A Zygo SWLI non-contact optical profilometer was used.

Table 8: Average Wear Track Depth (micrometers)

	Bearing Material	
Test Specimen	Aluminum 6061 T6	Torlon 5030
Avalon 89	< 1	<1
Rulon LR	3.2	26.9

4.0 Discussion

As seen in sections 3.1 and 3.3 the result of the tensile and creep tests coincided very well with the available published data from the supplier, Solvay. This gave confidence that the material provided was free of defects and that the test methods could be performed accurately and repeatedly.

The results of the tension/tension fatigue test, while not an exact comparison to data found in the Solvay design guide, were in a reasonable range. Based on testing conducted at UConn, when subjected to a maximum stress of 8 kpsi at 15 Hz, the fatigue strength would surpass 10 million cycles. The high strength Torlon polymers (5030 and 7130) offer great fatigue strength at room temperatures. Fatigue test performance is quite high compared to the majority of polymers currently available.

As is the case with any anisotropic material, the fiber orientation has a direct impact on the material properties. Section 3.2 detailed the tensile strength behavior of material that was in either the longitudinal or transverse fiber orientation. Material in the longitudinal direction had an average tensile strength of 27.5 kpsi. Conversely, transverse fiber orientation led to an average decrease of 23% or to 21.2 kpsi. It is also important to note that these bars were machined out from injection molded sheets. The machining post injection molding degrades the tensile strength compared to individual injection molded bars due to the introduction of surface defects. In addition, it is not expected that the

degree of fiber alignment would be the same in a 6 by 6 inch molded sheets compared to the 6 by 0.50 inch gauge width injection molded tensile bars. This lower degree of alignment would be expected to, and did, result in a lower Young's modulus in the aligned direction for the larger injection molded sheet compared to the tensile bars and is not significantly affected by the machining damage. The tensile bars have both a higher modulus and tensile strength consistent with the idea that the narrower mold creates a higher degree of fiber alignment.

After achieving the baseline tensile strength data the next goal was to explore potential issues not discussed in the *Torlon Design Guide*. This involved exposing the Torlon 5030 samples to heavy moisture environments of water or Jet A. After soaking samples for various amounts of time, tensile testing was conducted to compare against the dry baseline data. Samples soaked to an average weight gain of 2.4% lost on average 15% of its original tensile strength when exposed to water. Samples that were soaked further to an average weight gain of 2.6% lost on average between 15 and 20% of its tensile strength. Accumulation of water moisture within Torlon 5030 will cause a decrease in tensile strength.

Conversely, the adverse effects of water exposure are not the same when Torlon 5030 is subjected to Jet A exposure. Section 3.5 detailed how samples that were soaked from a period of two to 22 weeks lost little or none of the original tensile strength properties. The absorption of Jet A is especially slow, similar to water. Samples that were directly soaked in Jet A for a period of 22 weeks, or to 0.418% weight gain, showed no tensile strength degradation. This is important as the organic components found in Jet A do not act as a solvent and degrade the material.

In order to alleviate problems associated with water absorption two potential avenues were explored, the first being drying out the samples after water exposure. Section 3.8 describes the effects of drying samples post water exposure at 350°F. Upon drying, samples returned to nearly the original properties. There were no observed issues with the samples after drying them at this temperature.

The second potential solution to prevent water absorption was to metallize the surfaces of the material. Section 3.10 details how adding a minimum layer of 1.0 mil copper and 0.5 mil nickel can decrease the absorption rate by nearly 80%. The more metal applied to the surface the better barrier it provides from moisture absorption.

However, a potential problem area when plating is the material surface itself. In a first plating trial the ends of the tensile bars had a rough surface where they were broken off from the injection mold. This roughened surface made it difficult to completely seal the surface from all pinholes. As a result, this provided an avenue for water moisture to gain access to the part. A second round of plating was conducted where all the edges and surfaces where made as smooth as possible.

Even when cleaning up the material surfaces, the electro-less copper metallization process is believed to leave pinhole areas on the surface. As a result, during the electroplating of nickel, significant charge is not achieved and the aforementioned pinholes are created. This is the probable reason behind the small, but continued water absorption in metallized parts.

In applications where there is water moisture and temperatures can suddenly rise to above 350°F blistering is a very probable scenario. At temperatures below 350°F it appears that the material behaves rather well and there are no signs of blistering.

Wear testing resulted in two distinct outcomes. In summary, Avalon 89 can be a possibly wear material to be used against Torlon 5030. Although it wore faster in the initial 40 hour break in rate, Avalon 89 actually wore slower on Torlon than Aluminum. For long term wear applications this could be a promising material combination. Conversely, Rulon LR progressively wore faster and more as the test ran on. This material would not be a wise selection as a wear material against bare Torlon 5030.

5.0 Future Testing

There are several areas that would be interesting to pursue following the work that was competed in this paper. The first would be expanded wear testing. A metallized coating is necessary to prevent water absorption, which ultimately leads to tensile strength degradation and the possibility of blistering. In conjunction, the metallized coating can act as an improved wear surface compared to bare Torlon and also as electromagnetic shielding. As a result, wear coatings should be developed and optimized for this material. One suggestion would be to look into a cobalt top layer as opposed to nickel. The cobalt offers improved wear characteristics and is also a more environmentally friendly material compared to using chrome. Also, when conducting the wear tests it would be interesting to lengthen the actual test time from 100 hours to 200 hours to get a more significant distribution of results.

Another material coating to look into is a form of nano nickel produced by Xtalic Corporation located in Marlborough, MA. The advantage to this nano nickel is that it offers five times the yield strength as the current nickel [6]. It is also quite ductile, which could lead to better adhesion should components be dented or hit with this coating. Another key benefit is that the Xtalic nano nickel is thermodynamically stable.

It would also be interesting to explore how evaporative plating performs over electro-less plating. The thought is that because the particles essentially rain down on the surface this may do a better job at covering the entire surface and preventing pinholes. The possible downside to evaporative coatings is a poorer adhesion to the Torlon surface.

Finally, in regard to coatings, waterproof sealants would also be a great avenue to pursue. If a waterproof sealant can be applied to the material in a dipping process this could ensure that all areas of the material can be sealed. Then, a layer of metal would only need to be applied to the wear surfaces as opposed to the entire material. One possible thought is a super hydrophobic coating developed by Ross Nanotechnology under the name Neverwet [7].

Another key area that should be explored is the effect of thermal cycling on Torlon 5030. Just from naturally being in the environment Torlon 5030 will absorb some degree of water depending on the humidity of the atmosphere. Upon drying it was discovered that the moisture leaves the material and the properties are returned to their original. It is a concern, however, exactly how continued thermal cycling could impact the material. It is possible that thermal cycling will lead to the material becoming more brittle.

Exploring blistering at a lower weight gain percent, such as less than 1.5%, would be interesting to explore. With a smaller degree of saturation it is possible that the water would be able to evaporate out of the part more quickly and safely at 400°F. Alternatively, this may just cause the part to blister less destructively.

High cycle and high temperature fatigue would also be an area to perform testing on. The concern with composite polymer materials is self-induced heating during high

frequency test environments. It is possible that the high frequency could soften the material and cause a failure well premature to its low frequency fatigue properties. Correspondingly, it would also be prudent to explore creep and room temperature fatigue performance of tensile samples where the fiber orientation is in the transverse direction. This is because in most applications the transverse type of load orientation will most likely occur and offers less performance compared to the longitudinal direction.

6.0 Conclusion

Overall, Torlon 5030 is a great material for a wide range of applications where high strength at elevated temperatures is needed. Its ability to be injection molded allows for intricate designs to focus on driving down cost and weight. The primary concern in using this material should be the environment that it is being used in. One must account for the tensile strength degradation as it absorbs moisture over time. While properties can be returned to their original strength, sudden temperature spikes above 350°F will promote blistering of the material regardless of the cross-sectional thickness.

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Appendix

Table 9: Dry Tensile Test Data

Material	Torlon 5030		Specimen S/N	Area	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	0.0621	33.7	2.45	2135
Test Location	UConn Materials Test Lab		T5030-2	0.0626	34.1	2.65	2119
Specimen Type	ASTM D638		T5030-3	0.0623	34.3	2.66	2095
Form	Injection Molded		T5030-4	0.0617	32.4	2.45	2099
Surface Finish	As-molded		T5030-5	0.0621	34.0	2.74	2078
Fiber Orientation	Flow		T5030-6	0.0618	33.9	2.77	2062
Test Temperature	78 F		**Average**		**33.7**	**2.62**	**2098**
Preconditioning	Dried 24 Hours at 300F		**Standard Dev.**		**0.6**	**0.13**	**24**
Test Environment	Ambient						

Table 10: Longitudinal Fiber Orientation

Material	Torlon 5030		Specimen S/N	Area	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	0.06825	29.5	3.28	1518
Test Location	UConn Materials Test Lab		T5030-2	0.06552	28.6	3.15	1541
Specimen Type	ASTM D638		T5030-3	0.06734	25.7	2.93	1425
Form	Injection Molded		T5030-4	0.06734	26.0	2.90	1487
Surface Finish	Machined to Dimensions		T5030-5	0.06812	27.5	2.69	1640
Fiber Orientation	Longitudinal		**Average**		**27.5**	**2.99**	**1522**
Test Temperature	77 F		**Standard Dev.**		**1.5**	**0.21**	**70.6**
Preconditioning	24 hours Post Re-cure						
Test Environment	Ambient						

Table 11: Transverse Fiber Orientation

Material	Torlon 5030		Specimen S/N	Area	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	0.06525	20.1	2.30	1184
Test Location	UConn Materials Test Lab		T5030-2	0.06552	20.6	2.35	1196
Specimen Type	ASTM D638		T5030-3	0.06565	19.4	2.04	1244
Form	Injection Molded		T5030-4	0.06604	21.6	2.49	1220
Surface Finish	Machined to Dimensions		T5030-5	0.06204	22.1	2.88	1175
Fiber Orientation	Transverse		T5030-6	0.06617	23.6	2.45	1369
Test Temperature	77 F		**Average**		**21.2**	**2.42**	**1231**
Preconditioning	24 hours Post 9 Day Re-cure		**Standard Dev.**		**1.4**	**0.3**	**65.7**
Test Environment	Ambient						

Table 12: Tension/Tension Fatigue R = 0.1

Material	Torlon 5030		Specimen S/N	Area	Frequency, Hz	Cycles	Max Stress, kpsi
Test Type	Fatigue Properties		T5030-1	0.0619	15	286,680	12
Test Location	UConn Materials Test Lab		T5030-2	0.0622	15	203,145	12
Speciment Type	ASTM D638		T5030-3	0.0621	15	689,214	10
Form	Injection Molded		T5030-4	0.0620	15	617,718	10
Surface Finish	As-molded		T5030-5	0.0623	15	9,476,543	9
Fiber Orientation	Flow		T5030-6	0.0626	15	2,322,689	9
Test Temperature	78 F						
Preconditioning	Dried 24 Hours at 300F						
Test Environment	Ambient						

Table 13: Jet A Exposure on Tensile Strength

Material	Torlon 5030		Specimen S/N	Weeks Submerged in Jet A	Weight Gain, %	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	17	0.336	32.1	2.31	2112
Test Location	UConn Materials Test Lab		T5030-2	17	0.305	30.4	2.10	2120
Specimen Type	ASTM D638		T5030-3	17	0.373	32.6	2.67	2049
Form	Injection Molded		T5030-4	22	0.413	33.8	2.84	2096
Surface Finish	As-molded		T5030-5	22	0.434	33.5	2.70	2117
Fiber Orientation	Flow		T5030-6	22	0.408	33.0	2.71	2091
Test Temperature	76 F							
Preconditioning	Soaking in Jet A							
Test Environment	Ambient							

Table 14: Water Exposure on Tensile Strength

Material	Torlon 5030		Specimen S/N	Weeks Soaking	Weight Gain, %	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	2	2.39	29.1	2.61	2057
Test Location	UConn Materials Test Lab		T5030-2	2	2.45	28.8	2.57	2027
Specimen Type	ASTM D638		T5030-3	2	2.42	28.9	2.65	2086
Form	Injection Molded		T5030-4	2	2.38	28.4	2.38	2089
Surface Finish	As-molded		T5030-5	2	2.35	28.1	2.46	2074
Fiber Orientation	Flow		T5030-6	5	2.60	28.6	2.39	2083
Test Temperature	77 F		T5030-7	5	2.61	28.8	2.55	2058
Preconditioning	Samples soaking in 176°F water		T5030-8	5	2.64	28.8	2.58	2069
Test Environment	Ambient		T5030-9	5	2.64	28.6	2.45	2075
			T5030-10	5	2.64	28.9	2.41	2104

Table 15: Effects of Drying at 350°F

Material	Torlon 5030		Specimen S/N	Weeks Soaked	Test Condition	Weight Gain, %	Tensile Strength, kpsi	Tensile Strain, %	Tensile Modulus, kpsi
Test Type	Tensile Properties		T5030-1	2	Wet	2.60	26.8	2.56	2061
Test Location	UConn Materials Test Lab		T5030-2	2	Wet	2.59	26.8	2.67	2005
Specimen Type	ASTM D638		T5030-3	2	Wet	2.60	26.8	2.49	2096
Form	Injection Molded		T5030-4	2	Post Drying	0.21	31.6	2.65	2084
Surface Finish	As-molded		T5030-5	2	Post Drying	0.20	31.7	2.71	2032
Fiber Orientation	Flow		T5030-6	2	Post Drying	0.20	31.8	2.54	2015
Test Temperature	78 F		T5030-7	5	Wet	2.88	26.6	2.51	2115
Preconditioning	Soaked in 176°F water and tested wet or after drying for 24 hours at 350°F		T5030-8	5	Wet	2.87	26.7	2.43	2074
Test Environment	Ambient		T5030-9	5	Wet	2.88	26.5	2.41	2016
			T5030-10	5	Post Drying	0.47	30.7	2.53	2042
			T5030-11	5	Post Drying	0.43	30.2	2.42	2089
			T5030-12	5	Post Drying	0.49	31.4	2.39	2014